Energy Efficient Constellation Size Design for Green Radios in Semi-blind Relay Networks

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***Abstract*—Green radios have drawn much attention in recent years. This paper derives the energy per good-bit expressions for semi-blind relay networks with and without maximum ratio combining under Rayleigh fading channels considering the energy consumed per bit as well as the link reliability and retransmission probabilities. The optimal constellation size is investigated constrained by a given bit error rate. The energy consumed in the transmission, reception and idle modes are all involved. Numerical simulations demonstrate the energy efficiency performance of semi-blind relay networks in several cases with the direct transmission as the benchmark. Finally some practical implications can be made from these observations. The analysis and results will be a good reference for the real green cellular communication design.**

I. INTRODUCTION

The next generation wireless communication promises higher data rates and diverse radio interfaces to provide all users with a continuous seamless connection. However, the battery capacity for the state-of-the-art handsets lags behind the surge in power requirements for these multimedia-rich and multi-standard services [1]. Meanwhile, greenhouse gas emissions leave a significant environmental footprint. Thus green communications have drawn much attentions in recent years. It will not only be beneficial for the global environment but also make commercial sense to gain sustainable profits [2]-[4].

New type network topologies envisage a prospective path to achieve green radios. The coexistence of femtocells and picocells with macro-cells can provide high speed access service for indoor user equipments (UEs) and enhance the throughput in hot spot areas [5]-[6]. Compared with power hungry macro base stations (BSs), the smaller more agile BSs can output very low power but achieve improved capacity through large scale deployments. Relay nodes (RNs) are connected with the core network by wireless backhaul links. It is easily deployed with low costs. Therefore, relay technique is viewed as an enabling technique to reduce the overall energy consumption.

As is known, the data transmission can be completed in a shorter period by using larger constellation sizes. But more power is radiated for transmission. On the contrary, smaller constellation sizes can reduce the radiation power. But more power is required for circuit and processing due to the increasing transmit time. Therefore, the specific modulation scheme will have an impact on the energy efficiency of relay networks. But limited works in the literature have covered this issue. The outage probability and symbol error rate in relay networks under various channel models have been extensively studied [7]-[9]. But no work has analyzed the energy efficiency in relay networks. The optimal constellation size for energy efficient relay transmission has yet to be exploited.

Motivated by these considerations, this paper analyzes the energy efficiency performance of a three-node relay network employing semi-blind relays under Rayleigh fading channels. Semi-blind relays does not require a continuous estimation of the channel state information (CSI) but only the statistical one about the backhaul link [8]. The energy per good-bit is used as the energy efficiency metric considering not only the energy consumed per bit but the link reliability and retransmission probabilities as well. The energy per good-bit expressions in semi-blind relay networks with and without maximum ratio combining (MRC) under Rayleigh fading channels are derived. Finally, numerical simulations reveal some interesting results with practical implications.

The rest of the paper is organized as follows. Section II describes the system model. Power consumption model is formulated in Section III. Section IV derives the energy per good-bit expressions for semi-blind relay networks with and without MRC under Rayleigh fading channels. Section V carries out computer simulations and analyze their practical indications. Section VI concludes the paper finally.

II. SYSTEM MODEL

We consider a relay-enhanced single cell system consisting of one BS/UE pair with one semi-blind RN. The cooperative transmission includes two phases. In the first phase, BS broadcasts an information packet with transmit power P_t. UE will first attempt to decode the signal to see if it can be received correctly. Otherwise, the second phase is initiated. RN amplifies what it received from the signal by the fixed gain and forwards it to UE with transmit power P_t. At the end of the second phase, if UE still fails to receive the signal correctly, BS will retransmit the signal until UE can receive it successfully. There exists a mechanism at the receiver that can identify when an error occurs. Then the feedback link will inform the transmitter to retransmit the particular signal if the error is detected. This is the Automatic Repeat-reQuest scheme with no retry limits. The number of retransmission is a geometric random variable and has a mean of $\frac{1}{p_{\mathrm{suc}}}$ [10]. p_{suc} represents the system success probability.

The channel is distributed as the zero-mean independent identically distributed complex Gaussian random variable with a combination of path loss and Rayleigh fading denoted as

$$|h_i|^2 = \alpha_i d_i^{-\beta}, \tag{1}$$

where $i = 0, 1, 2$ represents the channel from BS to UE, from BS to RN and from RN to UE respectively. α_i is the Rayleigh fading coefficient. d_i denotes the distance between two nodes. β denotes the path loss exponent. The channel remains constant during one information packet but is independent from one packet to another.

Then the signal-to-noise ratio (SNR) in each link obeys the exponential distribution with the mean $\bar{\gamma}_i = \frac{P_t \sigma_i^2}{N_0 B d_i^{\beta}}$, where σ_i^2 is the average fading power. N_0 is power spectral density of the noise. B is the system bandwidth. The instantaneous SNR in each link is represented as $\gamma_i = \frac{\alpha_i P_t}{N_0 B d_i^{\beta}}$. Thus the instantaneous end-to-end equivalent SNR at UE can be written as

$$\gamma_{\mathrm{eq}} = \frac{\gamma_1 \cdot \gamma_2}{\gamma_2 + C}, \tag{2}$$

where $C = \frac{\bar{\gamma}_1 \exp\left(-\frac{1}{\bar{\gamma}_1}\right)}{E_1\left(\frac{1}{\bar{\gamma}_1}\right)}$ is the fixed gain [8]. $E_1(x) = \int_x^{+\infty} \frac{e^{-t}}{t} dt$ is the first-order exponential integral function.

III. POWER CONSUMPTION MODEL

The power consumption of BS and RN is composed of three modes: transmission, reception and idle. The power consumed in each mode is denoted as $\frac{P_t}{\eta} + P_{ct}$, P_{cr} and P_{idle} accordingly, where P_t is the transmit power. $\eta = \frac{\xi}{\psi} - 1$ denotes the power amplifier (PA) efficiency. ψ is the drain efficiency of PA. $\xi = 3\frac{\sqrt{M}-1}{\sqrt{M}+1}$ is the peak-to-average power ratio assuming the uncoded Multiple Quadrature Amplitude Modulation (MQAM) is adopted [11].

The circuit power mainly generates from the radio frequency circuits. They include the frequency synthesizer, low-noise-amplifier and some filters [12]-[13]. For simplicity, these modules are classified into Transmit Electronic P_{ct} and Receive Electronic P_{cr} [14]. After the transmission, BS or RN switches to the idle mode. When BS or RN is switched off, the power consumption should be lower than that in transmission or reception. That is $P_{\mathrm{idle}} \le P_{ct}$ and $P_{\mathrm{idle}} \le P_{cr}$. Superscripts $(\cdot)^{BS}$ and $(\cdot)^{RN}$ will be used to represent the power consumption at BS and RN, respectively. As relay is a low cost site, its power consumption in each mode is smaller than that of BS.

IV. ENERGY EFFICIENCY ANALYSIS

The L-bit information packet is transmitted to UE within a hard deadline T. If the uncoded MQAM is adopted as the modulation scheme, the minimum required transmission time is

$$T_{\mathrm{on}} = \frac{L}{bB}, \tag{3}$$

where $b = \log_2 M$ is the constellation size for a specific MQAM scheme. The duration of the idle mode is

$$T_{\mathrm{idle}} = T - T_{\mathrm{on}} \tag{4}$$

The outage probability is defined as the probability that the received SNR at UE drops below a protection ratio γ_{th}. It depends on the given bit error rate (BER) with the transmit power specified. For the uncoded square MQAM, the SNR γ_b to satisfy the required BER in the additive white Gaussian noise channel is [11]

$$p_b = \frac{1 - \left(1 - \frac{2\left(\sqrt{M}-1\right)}{\sqrt{M}} Q\left(\sqrt{\frac{3b\gamma_b}{M-1}}\right)\right)^2}{b} \tag{5}$$

The SNR threshold γ_{th} is therefore derived as

$$\gamma_{\mathrm{th}} = \frac{E_b}{N_0 T_b} = \gamma_b B \log_2 M, \tag{6}$$

where E_b is the signal energy per bit. T_b is the bit time assuming the symbol time $T_s = \frac{1}{B}$.

A. Direct Transmission

The system success probability of the direct transmission can be calculated as

$$p_{\mathrm{suc,direct}} = p\left(\gamma_0 \ge \gamma_{\mathrm{th}}\right) = e^{-\frac{N_0 B d_0^{\beta} \gamma_{th}}{P_{\mathrm{t}} \sigma_0^2}}. \tag{7}$$

Therefore considering the link reliability and retransmission probabilities, the energy per good-bit for the direct transmission is derived as

$$E_0 = \frac{\left(\frac{P_t^{BS}}{\eta} + P_{ct}^{BS}\right) T_{\mathrm{on}} + P_{\mathrm{idle}}^{BS} T_{\mathrm{idle}}}{L \cdot p_{\mathrm{suc,direct}}}. \tag{8}$$

B. Semi-blind relay with non-MRC

For the semi-blind relay without MRC, if the outage event occur in the BS-UE link, UE only utilizes the signal received from RN for decoding. Then the probability that γ_{eq} falls below γ_{th} is calculated by [8]

$$p\left(\gamma_{\mathrm{eq}} \le \gamma_{\mathrm{th}}\right) = 1 - 2\sqrt{\frac{C\gamma_{\mathrm{th}}}{\bar{\gamma}_1 \bar{\gamma}_2}} e^{-\gamma_{\mathrm{th}}/\bar{\gamma}_1} K_1\left(2\sqrt{\frac{C\gamma_{\mathrm{th}}}{\bar{\gamma}_1 \bar{\gamma}_2}}\right), \tag{9}$$

where $K_1(\cdot)$ is the first order modified Bessel function of the second kind. The system success probability of the cooperative transmission without MRC is derived as

$$p_{\mathrm{suc\_nonMRC}} = 1 - p\left(\gamma_0 \le \gamma_{\mathrm{th}}\right) p\left(\gamma_{\mathrm{eq}} \le \gamma_{\mathrm{th}}\right). \tag{10}$$

Then the average transmit power for the cooperative transmission without MRC is

$$\begin{aligned} P_{\mathrm{w/oMRC}} = &\left(\frac{P_t^{BS}}{\eta} + P_{ct}^{BS} + P_{cr}^{RN}\right) p\left(\gamma_0 \ge \gamma_{\mathrm{th}}\right) \\ &\left(\frac{P_t^{BS}}{\eta} + P_{ct}^{BS} + P_{cr}^{RN} + \frac{P_t^{RN}}{\eta} + P_{ct}^{RN}\right) p\left(\gamma_0 \le \gamma_{\mathrm{th}}\right) \end{aligned} \tag{11}$$

where the first term corresponds to the power consumption when the destination correctly decodes the signal from the source. The second term corresponds to the power consumption when the BS-UE link is in outage and the relay helps to forward the signal. Then the energy per good-bit for the cooperative transmission without MRC can be derived as

$$E_1 = \frac{P_{\mathrm{w/oMRC}} T_{\mathrm{on}} + \left(P_{\mathrm{idle}}^{BS} + P_{\mathrm{idle}}^{RN}\right) T_{\mathrm{idle}}}{L \cdot p_{\mathrm{suc\_nonMRC}}}. \tag{12}$$

In order to measure the energy efficiency improvement by introducing semi-blind relays in the network, the cooperative gain is defined as

$$G_1 = \frac{E_1}{E_0}. \tag{13}$$

C. Semi-blind relay with MRC

For semi-blind relays with MRC, it is assumed that the destination knows the CSI of each link. The destination combines the signals from the relay and the source to output the maximized equivalent SNR γ, i.e.,

$$\gamma = \gamma_{\mathrm{eq}} + \gamma_0. \tag{14}$$

The average power consumption for semi-blind relay with MRC is equal to Eq. (11). Then the system success probability in this case is given by

$$p_{\mathrm{suc\_MRC}} = 1 - p\left(\gamma_0 \le \gamma_{\mathrm{th}}\right) p\left(\gamma_{\mathrm{eq}} + \gamma_0 \le \gamma_{\mathrm{th}}\right). \tag{15}$$

The probability that γ_{eq} falls below γ_0 conditioned on $\gamma_{\mathrm{s,d}}$ is derived as

$$\begin{aligned} & p\left(\gamma_{\mathrm{eq}} \le \gamma_{\mathrm{th}} - \gamma_0\right) \\ & = 1 - 2\sqrt{\frac{C(\gamma_{\mathrm{th}}-\gamma_0)}{\bar{\gamma}_1\bar{\gamma}_2}} e^{-(\gamma_{\mathrm{th}}-\gamma_0)/\bar{\gamma}_1} K_1\left(2\sqrt{\frac{C(\gamma_{\mathrm{th}}-\gamma_0)}{\bar{\gamma}_1\bar{\gamma}_2}}\right) \end{aligned} \tag{16}$$

Then averaging (16) over γ_0 we derive

$$\begin{aligned} & p\left(\gamma_0 + \gamma_{\mathrm{eq}} \le \gamma_{\mathrm{th}}\right) \\ & = \int_0^{\gamma_{\mathrm{th}}} p\left(\gamma_{\mathrm{eq}} \le \gamma_{\mathrm{th}} - \gamma_0 | \gamma_0\right) f\left(\gamma_0\right) d\gamma_0, \end{aligned} \tag{17}$$

where $f\left(\gamma_0\right) = \frac{N_0 B d_0^{\beta}}{P_{\mathrm{t}}\sigma_0^2} e^{-\frac{N_0 B d_0^{\beta}}{P_{\mathrm{t}}\sigma_0^2}\gamma_0}$. Then similar to the cooperative transmission without MRC, the the energy per good-bit and the corresponding cooperative gain in this case is derived.

V. SIMULATION RESULTS

In this section, the energy efficiency performance of semi-blind relay networks is presented by simulations. The optimal constellation size is investigated. The values of energy per good-bit in the simulation results are expressed in decibel. The large-scale relay pass-loss model is used to model the wireless links including BS-UE link, BS-RN link and RN-UE link [15]. The pass-loss of each link is represented as $\log_{10}|h_0|^2 = 128.1 + 37.6\log_{10}(d_0)$, $\log_{10}|h_1|^2 = 124.5 + 37.6\log_{10}(d_1)$ and $\log_{10}|h_2|^2 = 140.7 + 36.7\log_{10}(d_2)$, respectively. The simulation parameters are listed in Table 1 according to [16]. BS, RN and UE are located on a straight line. RN locates in the middle between BS and UE. First we focus on the energy efficiency performance of symmetric semi-blind relay networks. That is σ_i^2 in each link is equal. Without loss of generality, we assume $\sigma_i^2 = 1$. All the results are averaged over 800 channel realizations.

Figure 1 shows the variation of the energy per good-bit with respect to the constellation size $b \in \{2, 4, 6, 8, 10\}$ in semi-blind relay networks without MRC under different distances between BS and UE, i.e., $d_0 \in \{50m, 250m, 500m, 750m, 1000m\}$. As shown in the figure, for the short BS-UE transmission distances e.g., $d_0 = 50m$ and $d_0 = 250m$, the energy per good-bit becomes lower as the constellation size increases. Thus the larger constellation size is always favorable in this case because the link reliability is always high at short BS-UE transmission distance whatever the constellation size is.

For the long BS-UE transmission distances, the energy per good-bit increases when the constellation size gets either large or small. The optimal constellation size exists to minimize the energy per good-bit. The reason is that the larger constellation size can transmit more bits in a single transmission and reduce the transmit time. But the link reliability is less robust against large and small scale fading. More retransmit energy is required and vice versa. Moreover the location of the optimal constellation size changes with the transmission distance. Specifically, the optimal constellation size is comparatively smaller with longer BS-UE distances.

Figure 2 compares the energy efficiency performance of semi-blind relay networks with the equivalent network deployed by CSI-assisted relays. It is recognized that CSI-assisted relay is advantageous than semi-blind relay with

TABLE I
SIMULATION PARAMETERS

Term	Definition	Value
β	path loss exponent	3
N_0	noise power spectral density	-90dBm
B	bandwidth	5MHz
T	deadline	1s
ψ	drain efficiency	0.35
L	information packet length	20000bits
p_b	BER	0.1
$P_t^{\mathrm{BS}}, P_t^{\mathrm{RN}}$	transmit power at BS and RN	60W,35W
$P_{ct}^{\mathrm{BS}}, P_{ct}^{\mathrm{RN}}$	transmit circuit power at BS and RN	15.34W,5.87W
$P_{cr}^{\mathrm{BS}}, P_{cr}^{\mathrm{RN}}$	receive circuit power at BS and RN	22.85W,10.09W
$P_{\mathrm{idle}}^{\mathrm{BS}}, P_{\mathrm{idle}}^{\mathrm{RN}}$	idle power at BS and RN	35.44W,1.77W

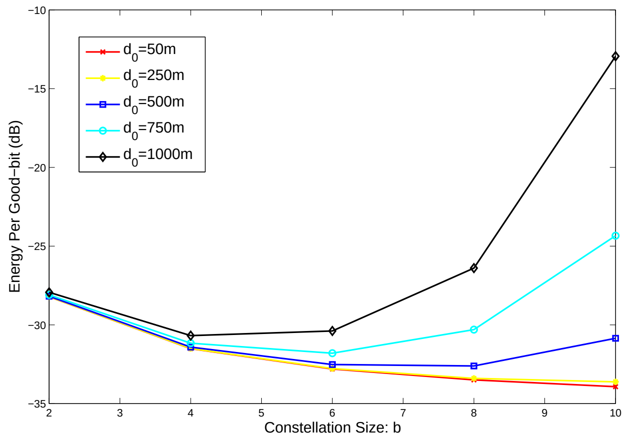

Fig. 1. Energy per good-bit against constellation size at different BS-UE distances

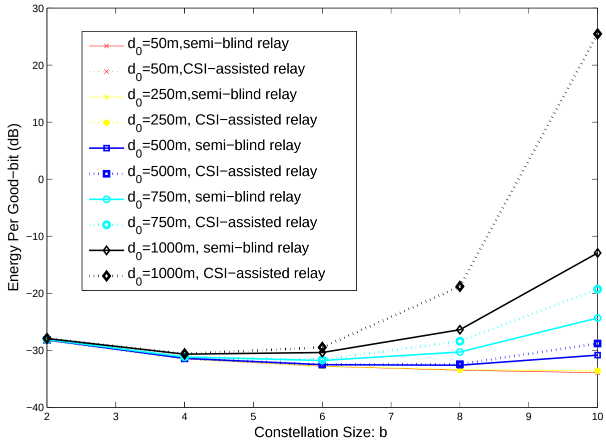

Fig. 2. Energy efficiency comparison between semi-blind and CSI-assisted relays

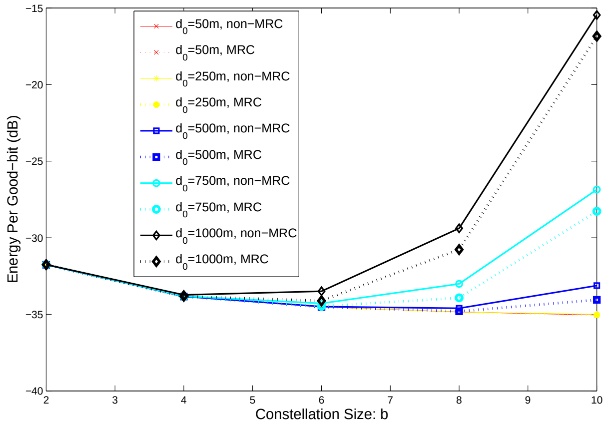

Fig. 3. Energy efficiency comparison of semi-blind relays with non-MRC and MRC techniques

respect to the outage probability and BER. But when the link reliability and energy efficiency are both considered, semi-blind relay consumed less energy per good-bit especially for large constellation size at long transmission distances.

Figure 3 compares the energy efficiency performance of non-MRC and MRC techniques in semi-blind relay networks. When the constellation size is small, their performance are almost the same. Thus non-MRC technique is more favorable due to its simplicity. When the constellation size becomes larger at long distances, MRC technique can improve the link reliability and is more energy efficient.

Figure 4 evaluates the energy efficiency performance of semi-blind relay networks with the direct transmission as the benchmark. When the transmission distance is short, the direct transmission is more energy-efficient because the introduction of RNs adds additional energy expenditure and counterbalances the energy saving from the increased link reliability. As the transmission distance increases, the superiority of RN becomes obvious. It shortens the transmission distance per hop and enhances the robustness against fading. Thus both the transmit and retransmit energies are saved.

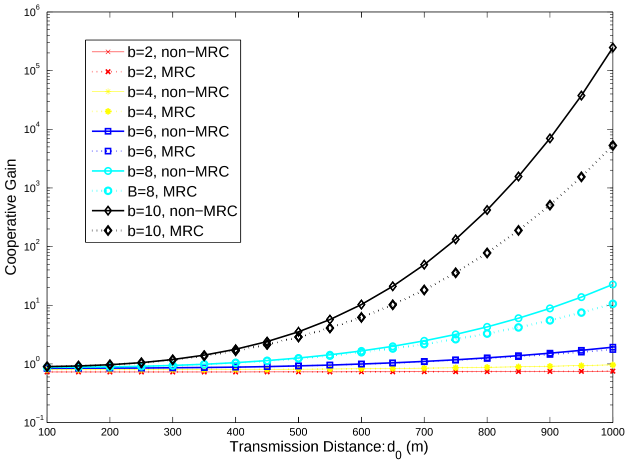

Fig. 4. Energy efficiency comparison between cooperative transmission and direct transmission

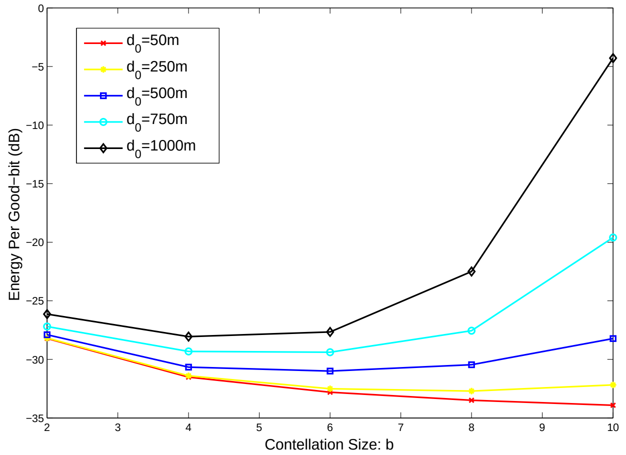

Fig. 5. Energy efficiency performance in the asymmetric semi-blind relay network with $\sigma_0^2 = 0.1, \sigma_1^2 = 1, \sigma_2^2 = 0.125$

Besides the similar observations in the symmetric semi-blind relay network, simulations in the asymmetric semi-blind relay network reveal some other interesting results. Figure 5 corresponds to $\sigma_1^2 > \sigma_2^2$. That is the fading of the backhaul link is not as severe as that in the access link. Figure 6 corresponds to $\sigma_1^2 < \sigma_2^2$. The energy consumed per good-bit in the asymmetric semi-blind relay network is larger than that in the symmetric semi-blind relay network. The channel fading variation has an impact on the system energy efficiency performance especially the backhaul link. When the channel condition in the backhaul link degrades more severely than the access link, the energy expenditure increases sharply. The channel condition in the backhaul link has a significant

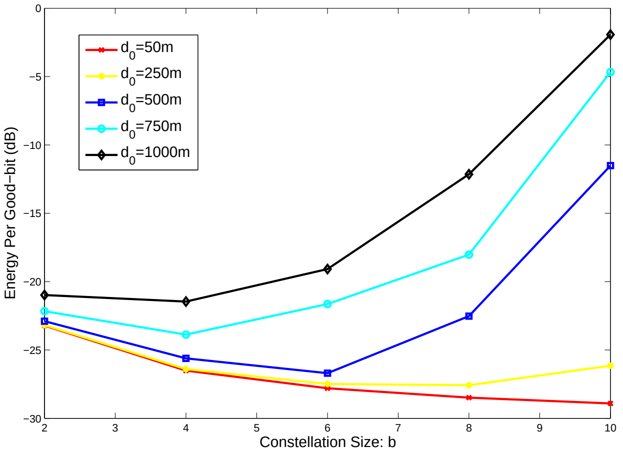

Fig. 6. Energy efficiency performance in the asymmetric semi-blind relay network with $\sigma_0^2 = 0.1, \sigma_1^2 = 0.125, \sigma_2^2 = 1$

influence on the system energy efficiency performance. Thus the backhaul link design is a bottleneck for the performance improvement of relay technique as a whole.

VI. CONCLUSION

In this paper the energy per good-bit expressions in the semi-blind relay network with and without MRC technique under Rayleigh fading channels constrained by the given BER are derived. We do not only consider the energy consumed during transmission, reception and idle period, but also consider the link reliability and the possibility for retransmission.

Numerical simulations performed in symmetric and asymmetric semi-blind relay networks reveal several interesting results with practical implications. First, the optimal constellation size exists for long transmission distances. But for the relatively short transmission distances, the larger constellation size is always favorable. The semi-blind relay is more energy efficient and more easily deployed than the CSI-assisted relay. Thus it is a potential better choice for the future green communication. Third, asymmetric relay networks consume more energy especially the degradation of the backhaul link. The backhaul link design will be a critical factor for the performance improvement of the relay technique.

Through our analysis and simulations, the effects of the constellation size, the transmission distance, the receiver diversity and the channel fading variation on the energy efficiency of semi-blind relay networks are presented. In order to get the most energy efficient relay networks, the system parameters should be carefully designed. While the analysis and conclusion would change due to the different power consumption model and parameters, the evaluation approach is promising for the more general case. The work in this paper is a good reference for the real cellular design.

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